

Hun τ ing for New Physics with Tau Decays

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(arXiv: 26XX.XXXX, in collaboration with Jure Zupan, Aparajitha Karthikeyan & Bhaskar Dutta)

Outline

- Introduction & motivation
- Tau induced proton decay in SMEFT
- Tau induced proton decay with BSM states
- Alternative search channels in Super-Kamiokande
- Summary & future work

Introduction


- The matter-antimatter asymmetry of the Universe remains one of the most intriguing puzzle to date.
- Baryon number violation is essential for generating this asymmetry [1].
- Several experiments have searched for BNV; including proton decay searches, baryon-number-violating (BNV) decays of charmed and bottom hadrons, tau leptons, and Z bosons.
- *No such process has been observed so far!*



Image credit: www.nobelprize.org/prizes/physics/2008


Motivation

- **Why tau decays?**

- Tau can decay into a wide variety of leptonic and hadronic states.
 - *Kinematic richness*  *Excellent probe of new physics (NP)*
- Access to complementary BNV channels (e.g. $\tau \rightarrow p \nu_\tau$) than proton decay searches ($p \rightarrow e^+ \pi^0$).

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- **The question is: can we observe BNV from tau decays?**

Heeck & Watkins [2]: Essentially, no! With Standard Model (SM) states.

- **In this work, we ask what about with BSM (Beyond SM) states?**

Tau Induced Proton Decay within SMEFT

- Operators that lead to BNV tau decays also induce proton decay.

➡ Any viable model must respect the stringent proton lifetime bound ($>10^{30}$ years) [3,4].

[3] SNO+ collaboration: 2205.06400 (hep-ex)

[4] SuperKamiokande collaboration: 2010.16098 (hep-ex)

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- $\Delta(B) \neq 0$ operators giving rise to nucleon decays start to appear at d=6 level in SM effective field theory (EFT) [5].

$$Q_{duq} = \varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C L_t^k],$$

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$$Q_{duu} = \varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$$

[q, L : quark, lepton $SU(2)_L$ doublets; u, d, e : quark, lepton singlets]

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[5] Weinberg: PRL,43(21):1566,1979

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➔ After electroweak symmetry breaking,

$$\mathcal{L}_\ell = C_{\ell t \alpha}^{AB} \bar{\ell}_t^c Q_\alpha^{AB}$$

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$$Q_{udu}^{AB} = [\bar{u}^c P_A d] P_B u$$

$$\alpha = \{udu, udd, uds, \dots\}; A, B : P_L, P_R$$

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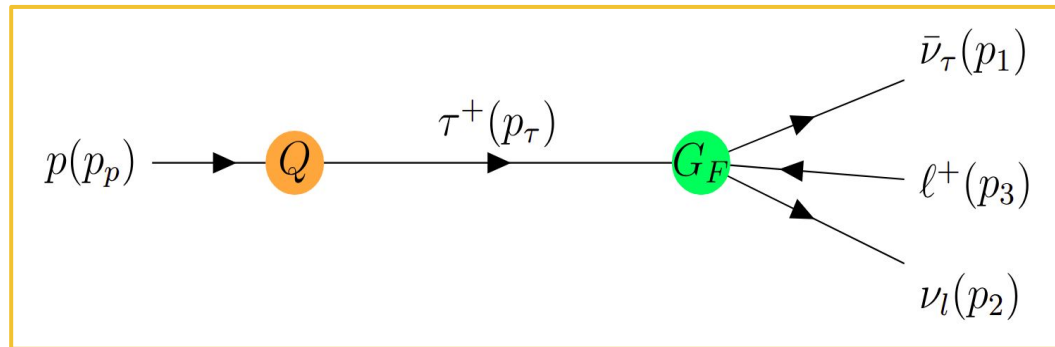
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$$\Lambda > 10^{10} \text{ GeV}$$

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Tau Induced Proton Decay with BSM states

Theoretical Framework:

- We explore the possibility of BNV tau decays with EFT operators including associated **dark final states (DS)**.

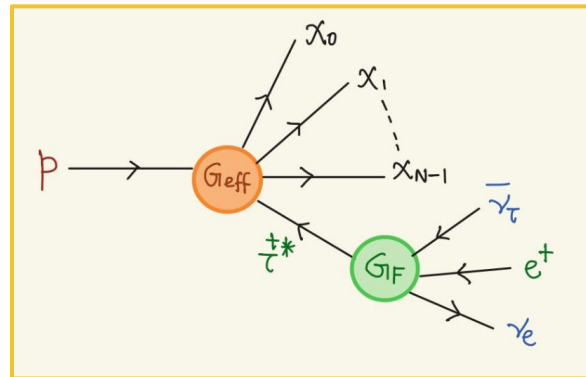
$$\mathcal{L} \supset G_{\text{eff}}(\bar{p}\chi_1)(\bar{\tau}\chi_0)(\chi_2\chi_3\cdots\chi_{N-1}) + \text{h.c.}, G_{\text{eff}} = 1/\Lambda^x$$

- One possible tau-induced proton decay channel is:

$$p \rightarrow (\tau^{+*} \rightarrow e^+ \nu_e \bar{\nu}_\tau) \chi_0 \chi_1 \cdots \chi_{N-1}$$

- Bound from average proton lifetime:

$$\tau_{(p \rightarrow e^+ + \text{anything})} > 0.6 \times 10^{30} \text{ years}$$



Bounds on the Effective Operators

1. Decay rate estimates from Naive Dimensional Analysis (NDA):

No. Proton decay channel	Decay rate scaling
1) $p \rightarrow (\tau^* \rightarrow e\nu_e\nu_\tau)\chi_1\chi_0$	$\Gamma \propto \frac{G_{\text{eff}}^2 G_F^2 Q^{11}}{8\pi \times (16\pi^2)^3 m_\tau^2}$
2) $p \rightarrow (\tau^* \rightarrow e\nu_e\nu_\tau)\chi_2\chi_1\chi_0$	$\Gamma \propto \frac{G_{\text{eff}}^2 G_F^2 Q^{13}}{8\pi \times (16\pi^2)^4 m_\tau^2}$
3) $p \rightarrow (\tau^* \rightarrow e\nu_e\nu_\tau)\chi_3\chi_2\chi_1\chi_0$	$\Gamma \propto \frac{G_{\text{eff}}^2 G_F^2 Q^{17}}{8\pi \times (16\pi^2)^5 m_\tau^2}$
4) $p \rightarrow (\tau^* \rightarrow e\nu_e\nu_\tau)\chi_5\chi_4\chi_3\chi_2\chi_1\chi_0$	$\Gamma \propto \frac{G_{\text{eff}}^2 G_F^2 Q^{23}}{8\pi \times (16\pi^2)^7 m_\tau^2}$

Typical momentum transfer: $Q \simeq \Delta E/N_f$

$$\Delta E = (m_p - \sum_i^{N_f} m_i)$$

Bounds on the Effective Operators

2. Verification of the scaling relations from MadGraph: Model I (2 DS)

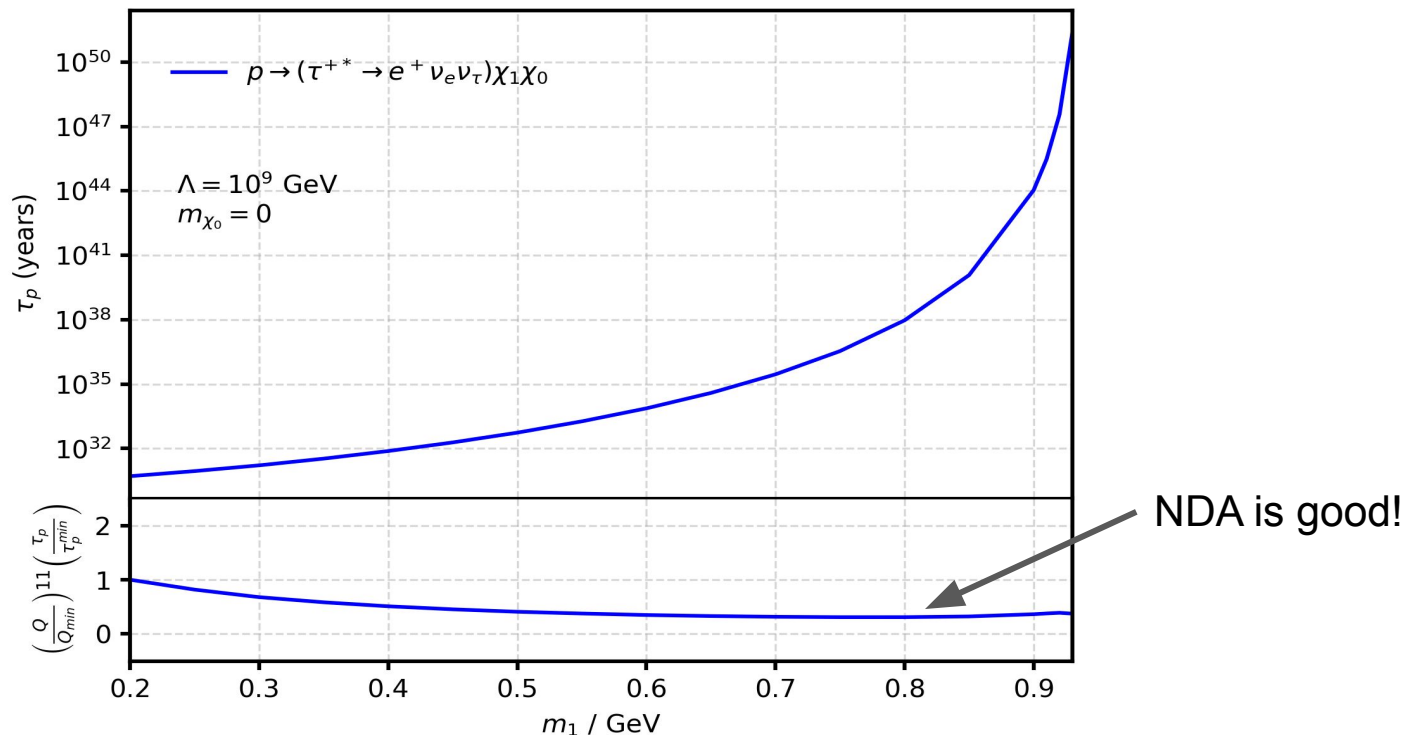


Figure 1: Estimates of lifetime of a free proton for 2 DS model as a function of χ_1 mass. The bottom panel illustrates the scaling of the lifetime with respect to the energy release $Q \propto (m_p - \sum m_\chi)$.

Bounds on the Effective Operators

2. Verification of the scaling relations from MadGraph: Model II (4 DS)

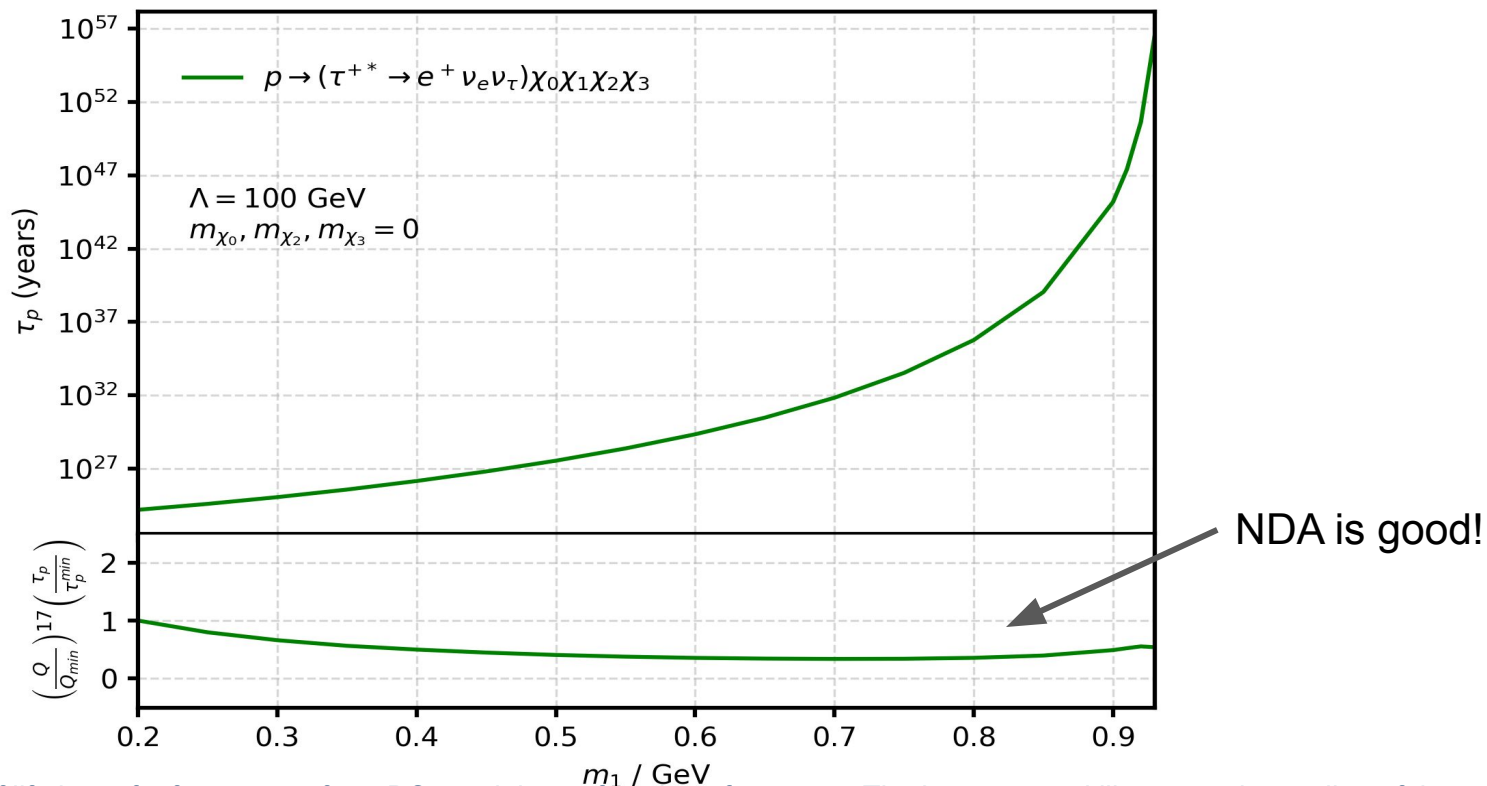


Figure 2: Estimates of lifetime of a free proton for 4 DS model as a function of χ_1 mass. The bottom panel illustrates the scaling of the lifetime with respect to the energy release $Q \propto (m_p - \sum m_\chi)$.

Bounds on the Effective Operators

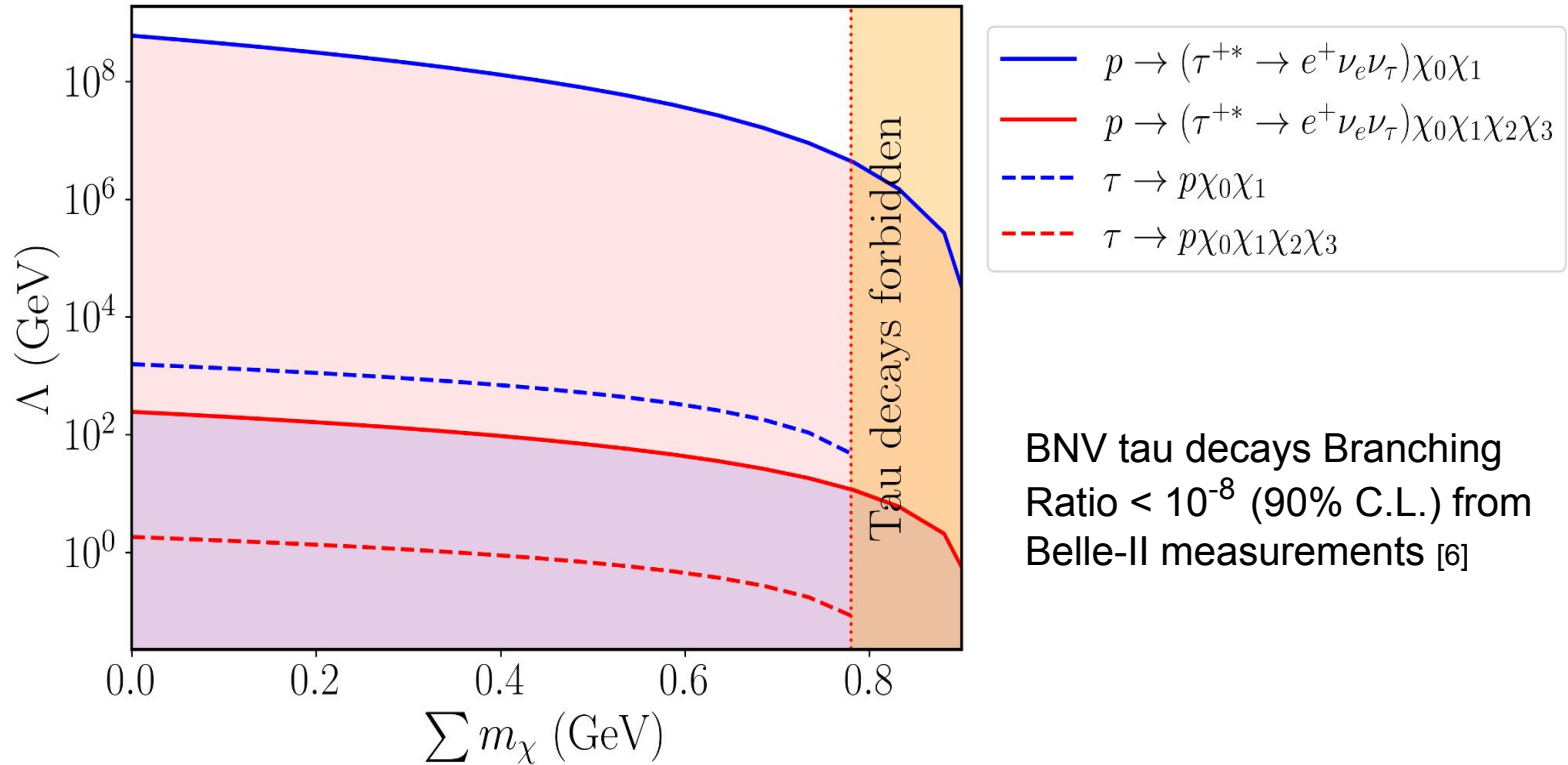


Figure 2: Bounds on the New Physics scale satisfying the proton lifetime & the corresponding observable tau decay bounds for the benchmark 2 DS and 4 DS models.

Branching Ratios for BNV Tau Decay Modes Involving DS

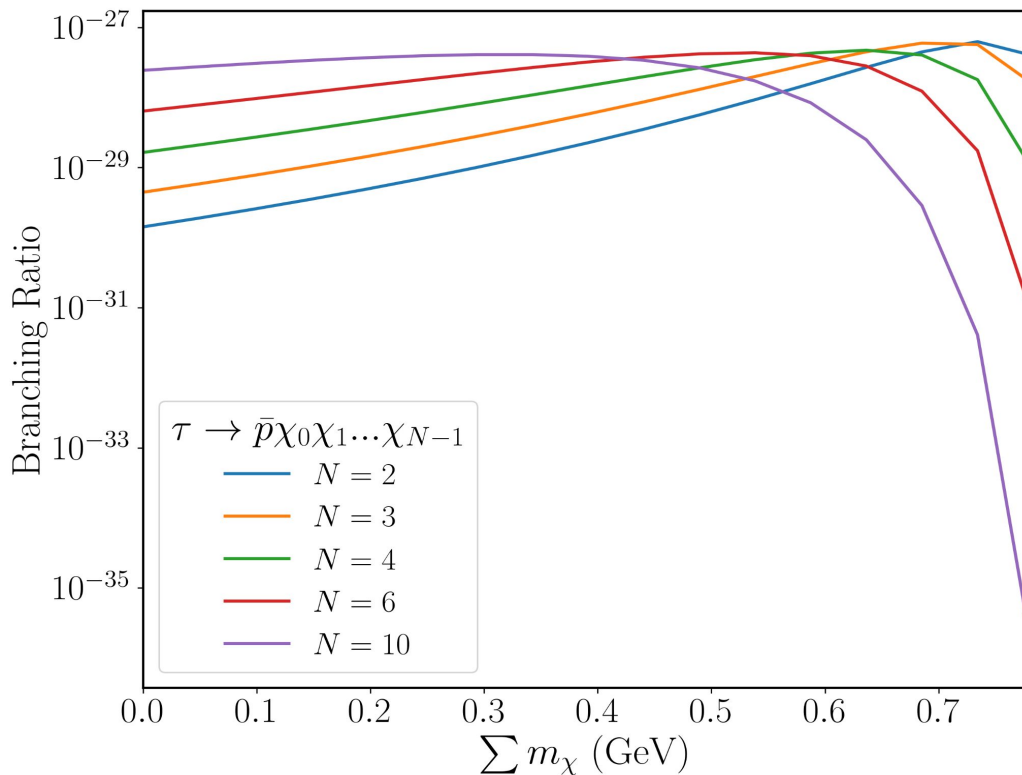
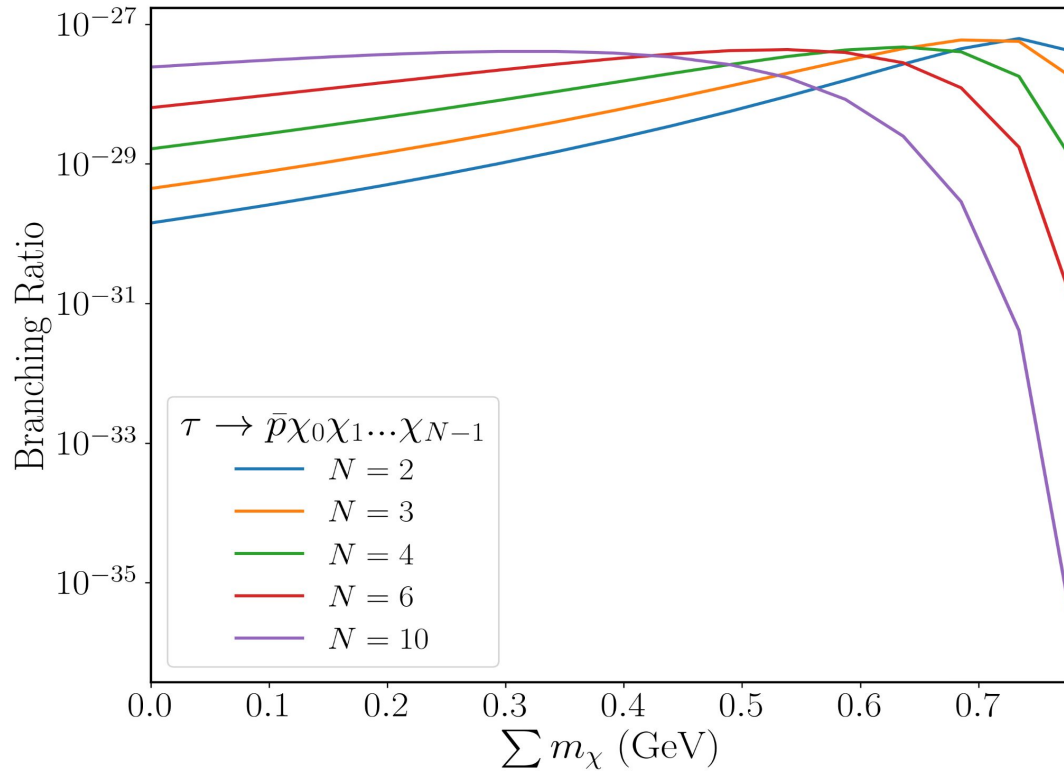


Figure 3: Branching ratios of BNV tau decay modes as a function of total mass of the final DS for different models

Branching Ratios for BNV Tau Decay Modes Involving DS



Extremely challenging to measure in the current and future experimental facilities, such as Belle-II (BR $\sim 10^{-8}$) for example!


Figure 3: Branching ratios (BR) of BNV tau decay modes as a function of total mass of the final DS for different models


Probing the models in Super-Kamiokande (SK)

- Proton decay searches at SK → most stringent constraint on BNV tau decays
- Hadronic modes (especially with pions) give clearer Cherenkov signatures → stronger bounds than leptonic modes → *provide a promising way to probe such models*

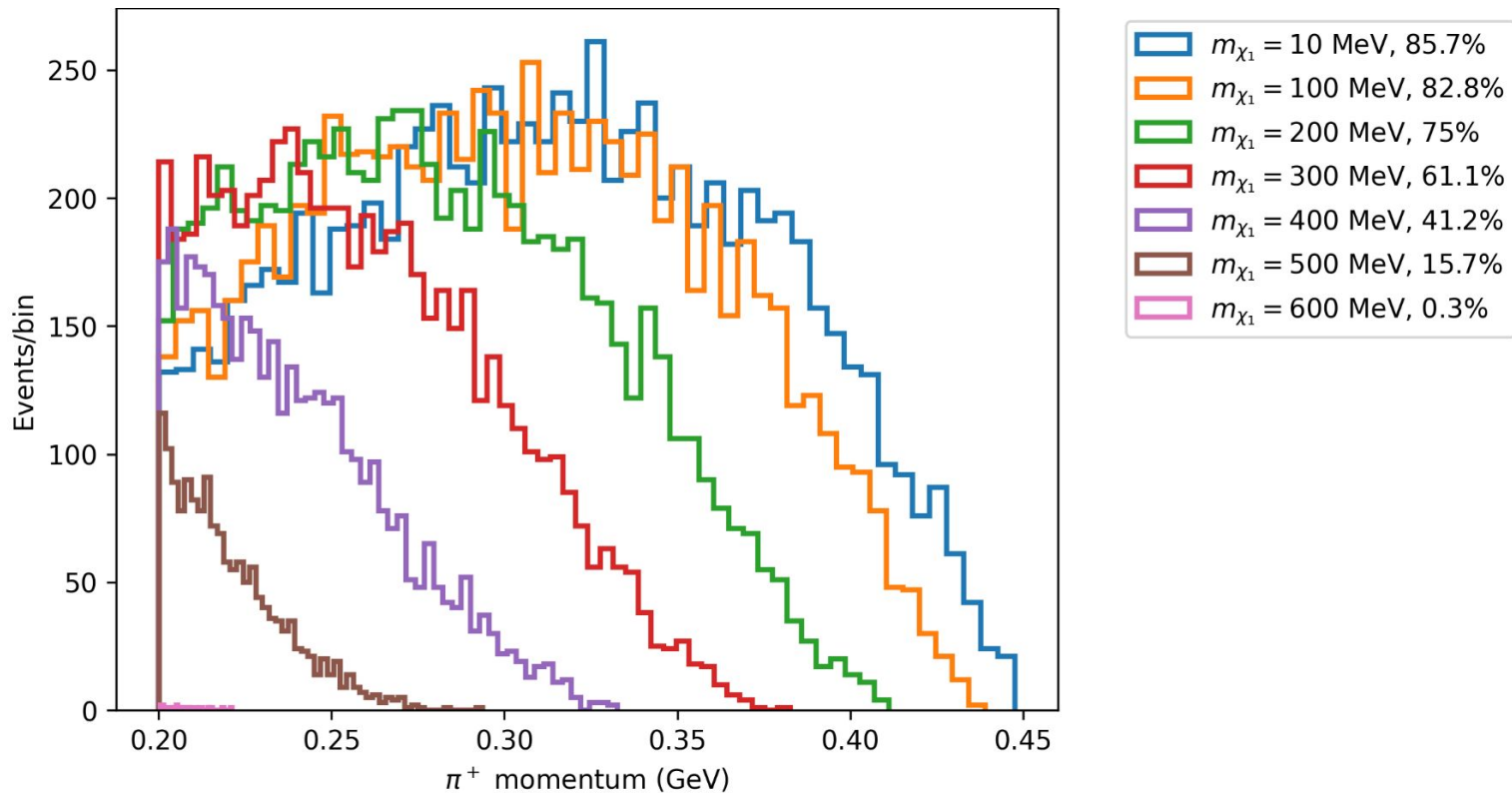
Probing the models in Super-Kamiokande (SK)

- Proton decay searches at SK \rightarrow most stringent constraint on BNV tau decays.
- **Hadronic modes (especially with pions) give clearer Cherenkov signatures** \rightarrow stronger bounds than leptonic modes \rightarrow *provide a promising way to probe such models.*
- We analyze the spectra of final state charged pions from the following processes:
 - **Benchmark Model I (2 DS):** $p \rightarrow (\tau^{+*} \rightarrow \pi^+ \nu_\tau) \chi_0 \chi_1$
 - **Benchmark Model II (4 DS):** $p \rightarrow (\tau^{+*} \rightarrow \pi^+ \nu_\tau) \chi_0 \chi_1 \bar{\chi}_2 \chi_3$

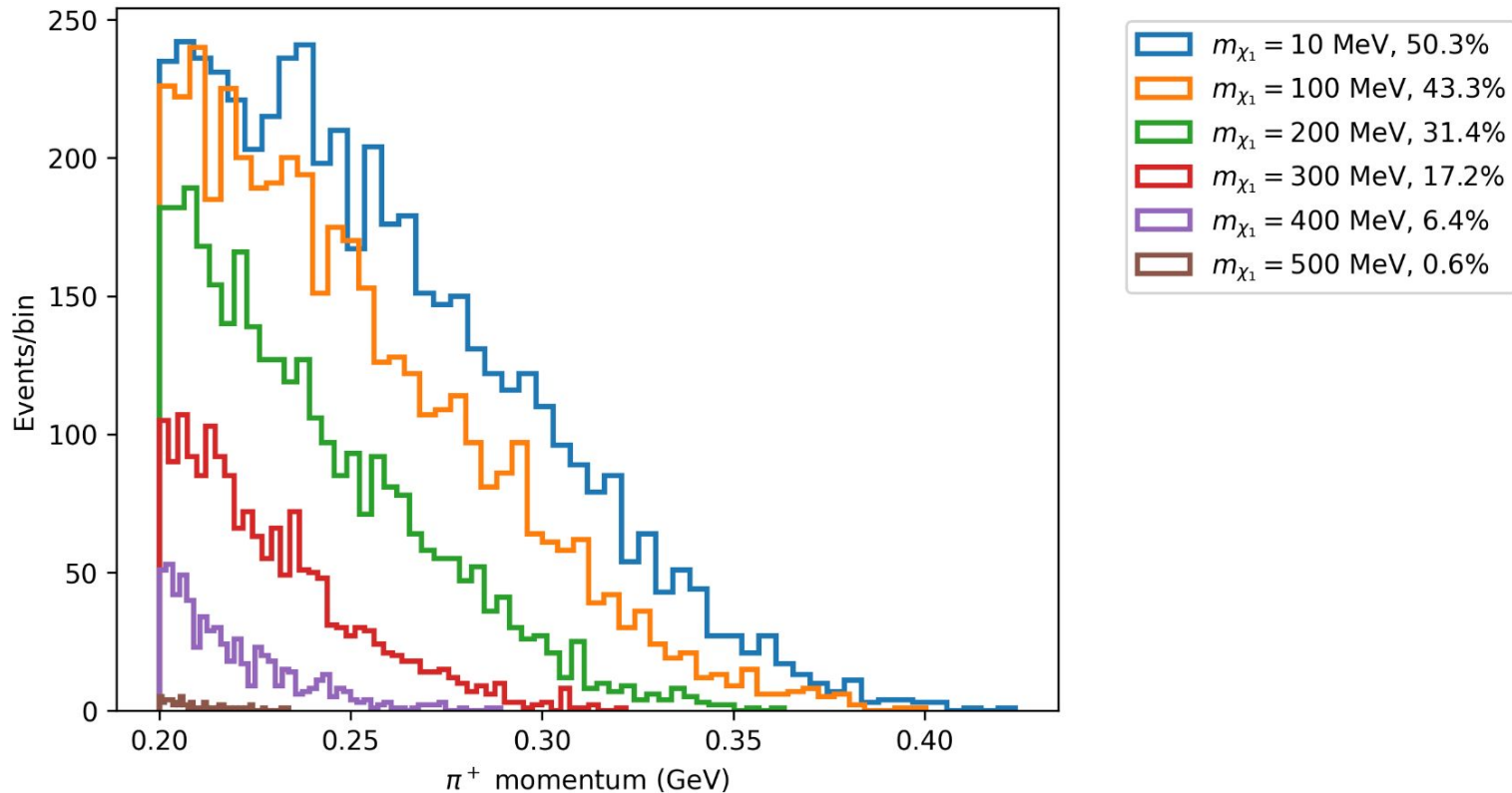
Model implementation (FeynRules: our model + TauDecay package) 

Analysis with Super-K selection cuts  Event generation (MadGraph5)

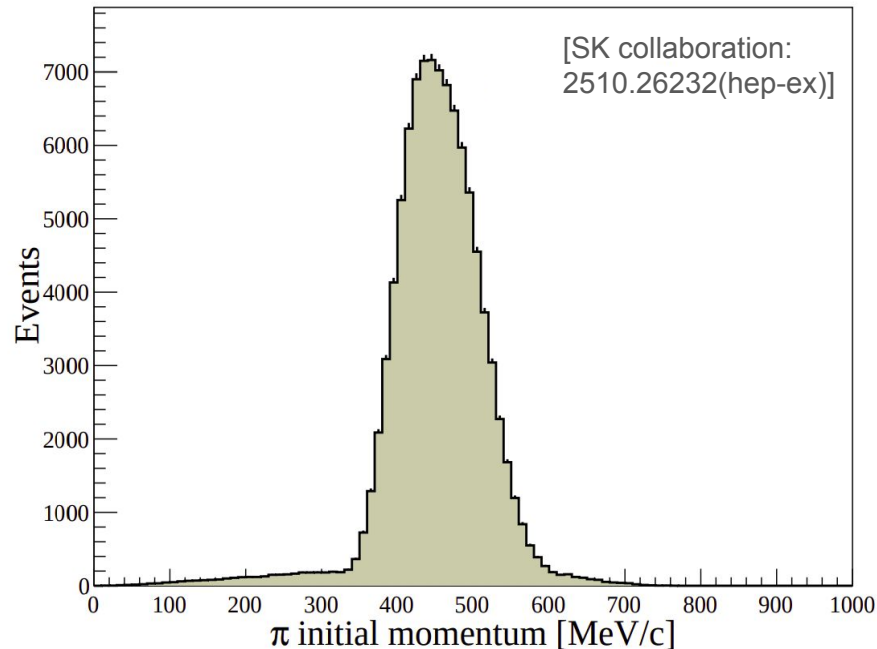
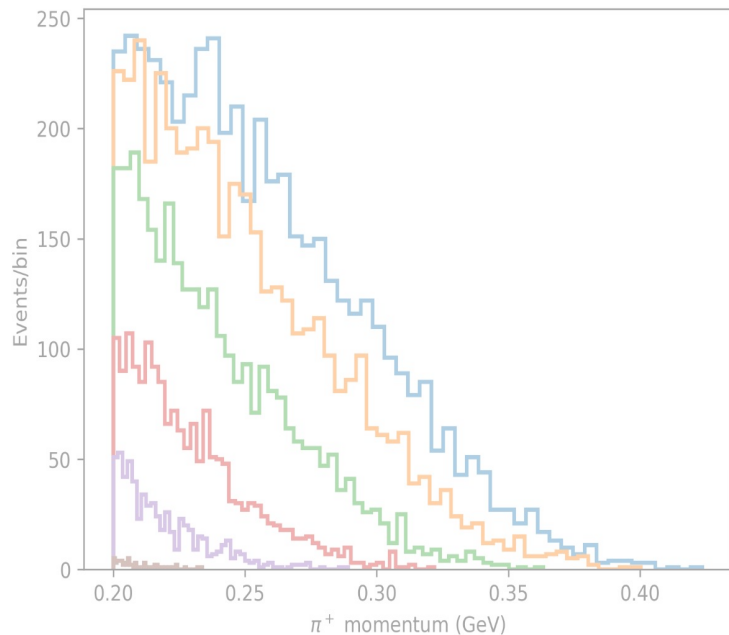
Charged Pion Spectra for Model I (2 DS)



Charged Pion Spectra for Model II (4 DS)



Charged Pion Spectra for Model II (4 DS)



Distinguishable feature from the usual two body proton decay search channel ($p \rightarrow \pi^+ \nu$) in Super-K !

Summary & Future Work

- Even including BSM states, proton decay bounds essentially beat any observable BNV tau decay limits; given the reach of current and near future experimental facilities (such as Belle-II for example).
- We are able to probe these types of models in proton decay experiments such as Super-Kamiokande.
- We are working on estimating the bounds for BNV tau decays involving the hadronic modes similar to the leptonic channels.
- The constraints might be more stringent in those scenarios.